Growth of Qinghai Tibetans Living at Three Different High Altitudes

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ABSTRACT This study compares the stature, weight, skinfolds, upper arm muscle area, and chest dimensions of Tibetan children, adolescents, and young adults who were born and raised, or who had lived from infancy, at 3,200 m, 3,800 m, and 4,300 m in Qinghai Province, People's Republic of China. While the individuals measured in Qinghai are among the tallest and heaviest Tibetans reported in the literature, they are nevertheless smaller and lighter than well-off children living at low altitude. The pattern of size variation among Tibetan males and females measured at the three high altitudes, along with evidence of a secular trend at 4,300 m, suggests that nutrition may significantly effect growth at high altitude. Only minor differences in thorax dimensions exist between Tibetan males and females measured at 3,200 m and 3,800 m. However, Tibetan males at 4,300 m possess slightly narrower and deeper chests (during and after adolescence) than males at 3,200 m and 3,800 m. Since individuals from 3,800 m and 4,300 m belong to the same local populations, this characteristic is unlikely to be genetically determined. However, it may be related to differences in the degree of hypoxia or to the influences of other environmental conditions. Am J Phys Anthropol 111:69–88, 2000.

Tibetan-speaking populations occupy a vast and diverse region in central Asia. These populations are subject to variations in altitude and environmental temperature, economic activities, diet, and health; and they are unlikely to be biologically homogeneous. It is therefore not surprising that children, adolescents, and adults in Tibetan-speaking groups show considerable variability in body size and other morphological phenotypes (Beall, 1981, 1984; Gupta and Basu, 1981, 1991; Ji and Ohsawa, 1993; Kuang, 1980; Malik, 1987; Malik and Pandey, 1993; Malik and Singh, 1978, 1984; Pawson, 1974, 1976, 1977a; Weitz, 1984). However, existing studies provide no systematic assessment of the extent to which differences in the morphological growth of children in Tibetan-speaking populations are influenced by the altitude at which they reside, by socioeconomic conditions, or by

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genetic differences that may exist between Tibetan populations (Beall, 1981). Clearly, it would be possible to investigate the influence of one of these variables, if variability in the others could be controlled. This is the strategy adopted in the present study, which investigates the growth of Tibetan children living at different altitudes while controlling the influence of biological (genetic) diversity and socioeconomic status. This strategy is made possible by the fact that culturally similar Tibetan populations now live in economically similar towns between 3,000–4,500 m in Qinghai Province in western China.

MATERIALS AND METHODS

The study area

Figure 1 shows the study area of eastern and central Qinghai Province, People's Republic of China. In 1982, Qinghai Province had a total population of slightly over 4 million, and a land area of 721 million km^2, of which 54% lies between 4,000–5,000 m, with an additional 24% between 3,000–4,000 m. As many as a half dozen linguistically and culturally different populations live in close proximity at altitudes between 3,000–4,500 m in Qinghai (Population Atlas of China, 1987); but three groups predominate in the Province: Tibetan, Han, and Hui. Unfortunately, there exist no studies that permit a determination of the degree to which these Qinghai populations represent different gene pools, or conversely, the extent to which they share similar biological origins. In the absence of genetic information on these groups, historical accounts of political events and population movements in eastern and central Qinghai can be used to indicate the extent to which Tibetan inhabitants of the region may have experienced gene flow from low-altitude groups (primarily Mongol, Turkic, and Han).

History

As early as 1400 BC, the Chinese used the name *Chiang* to refer to Tibetan tribal groups that inhabited the Tibetan-Qinghai Plateau and adjacent areas, and also to some Turkic and Mongol groups living in the northern and eastern regions of the Plateau (Bowles, 1935; Rock, 1956; Stein, 1972). But historical accounts dealing directly with the residents around Koko Nor (Qinghai Lake) do not appear to exist until about the 5th century AD. At that time, northern and eastern Qinghai were inhabited by a Turkic-Mongol group called the *Tu-yu-hun* by the Chinese (or the *Asha* by Tibetans). In the 6th and 7th centuries AD, the Tu-yu-hun periodically raided Tang Dynasty outposts in Gansu, prompting a series of military actions by the Chinese (Bowles, 1935; Grousset, 1970; Rock, 1956; Stein, 1972). At the same time, the Central Tibetan kingdom began to expand to the east towards Tang Dynasty China and to the north towards the Tu-yu-hun, incorporating autonomous Tibetan and Turkic tribal groups as they did so (Richardson, 1984). Around 635 AD, the Central Tibetan kingdom initiated a series of campaigns against the Tu-yu-hun, which ended when the latter took an oath of loyalty to the former in 670 AD (Shakapba, 1967). After this time, the area north and east of Koko Nor was administered by representatives of the Central Tibetan kings; and migrants from Central Tibet began to marry into the Tu-yu-hun population (Stein, 1972). At the beginning of the 9th century, as the power of the Central Tibetan kingdom declined, the strategic importance of eastern Qinghai to the Chinese diminished, and historical references are limited (Shakapba, 1967; Stein, 1972). In the 9th and 10th centuries, the area must still have been controlled to some extent by local Tibetan rulers, since they sent tribute to various Chinese emperors (Stein, 1972). But this was also a period when Turkic populations living to the north and west of Qinghai episodically entered the area (Bowles, 1935; Ekvall, 1939). At the beginning of the 11th century, eastern Qinghai was incorporated into the kingdom of Hsi-Hsia under the Tanguts, a population of Tibetan-Mongol origins (Bowles, 1935; Grousset, 1970; Huc and Gabet, 1928; Rock, 1956). This kingdom subsequently was conquered by the expanding Mongol empire under Ghengis Khan in the 13th century. Early in the 17th century, as the Manchus began the conquest of Mongolia, the Khoshut Mongols migrated into

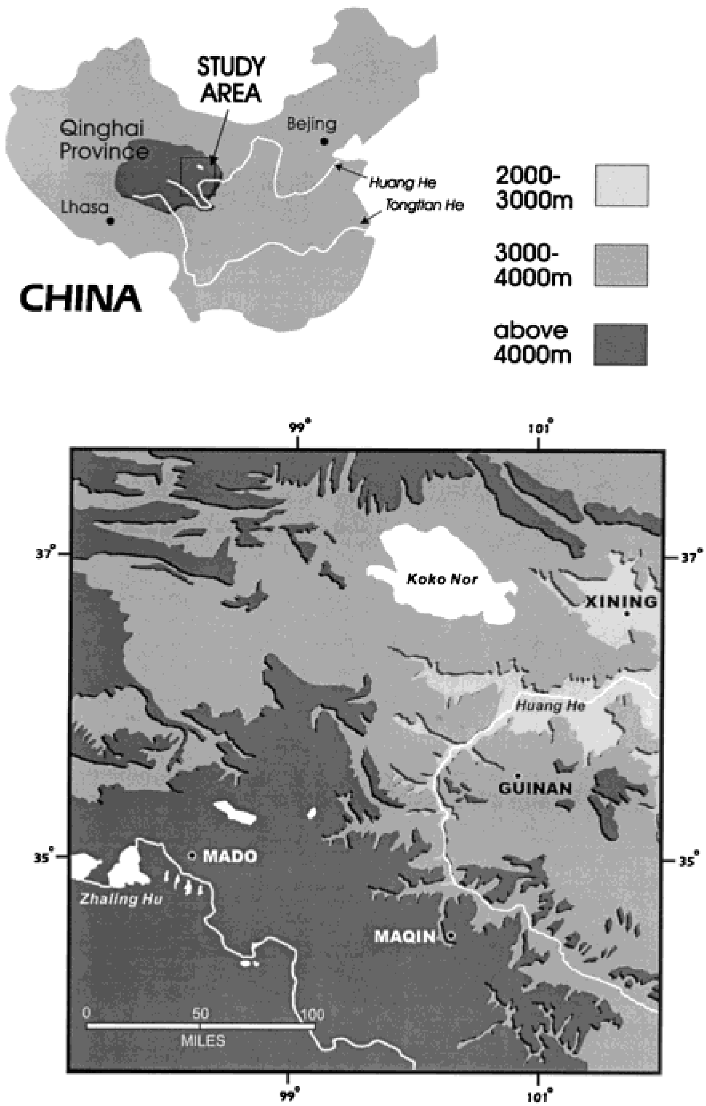

Fig. 1. Study area in Qinghai Province, People's Republic of China. Towns in which the study took place are located at 3,200 m (Guinan), 3,800 m (Maqin), and 4,300 m (Mado).

the Koko Nor region from the Lake Zaisan area just to the west of northern Xinjiang Province (Grousset, 1970). Subsequently, this group became allied with the 5th Dalai Lama, eliminated the opponents of Gelugpa Buddhism, and established control over most of Tibet and the region around Koko Nor (Grousset, 1970; Richardson, 1984). In Qinghai, they settled in the fertile pastures around the lake, and forced local Tibetan residents to move to areas south of the Huang He (Yellow River). During the late 17th and early 18th centuries, political relations between the Khoshut Mongols and China deteriorated, culminating with the conquest of the Mongols by Qing armies in 1724. Afterwards, several Mongol groups fled south and east of the Huang He into areas traditionally inhabited by Tibetans (Bulag, unpublished; Grousset, 1970). Even in recent times, groups living in this area have been characterized as Mongolian, despite the fact that they spoke a Tibetan dialect and dressed indistinguishably from Tibetans (Ekvall, 1939; Rock, 1956). During the 19th century, Tibetan groups that had

been forced to move south of the Huang He some 200 years earlier reentered the Koko Nor region and engaged in a type of guerilla warfare against the Mongols who remained in the area: raiding settlements, driving off livestock, and kidnapping children (Bulag, unpublished). By the end of the 19th century, both Tibetans and Mongols were permanently settled in the Koko Nor region under Qing colonial rule.

Unlike Tibetans living around Koko Nor and in the region south and east of the Huang He, the inhabitants of south-central Qinghai (west of the Huang He) are unlikely to have experienced significant admixture from low-elevation populations. This part of Qinghai consists of isolated high-altitude prairies, transected by mountain ranges. Even though this region has been politically part of China since the Yuan (Mongol) dynasty (1260–1368 AD), it was of little economic value and therefore largely ignored by Chinese governments until the mid-20th century (Ekvall, 1939; Rock, 1956; Rockhill, 1891; Rowell, 1983). The Tibetans that inhabit this area are known as *Goloks*, and may be descended from 7th century invaders from Central Tibet and from nomadic clans that have existed in the high-altitude areas of Central Qinghai at least as far back as the first century BC, when they were encountered by the Chinese as the Han Empire expanded westward (Ekvall, 1939; Rock, 1956; Rockhill, 1891; Rowell, 1983; Stein, 1972). Golok Tibetans are often described as being physically distinct from the Tibetan groups that live east of the Huang He (Rockhill, 1891; Ekvall, 1939), and have been classified physically as part of the larger Central Tibetan population (Bowles, 1935). Furthermore, they appear to be linguistically different from Tibetans living in eastern Qinghai (Ekvall, 1939; Huc and Gabet, 1928; Rockhill, 1891); and their language may include elements from the 7th century Lhasa dialect (Ekvall, 1939). Thus, Golok Tibetans represent a population with a lengthy high-altitude ancestry, and one that also may be genetically dissimilar from Tibetans inhabiting northeastern Qinghai (around Koko Nor) and those living in the area south and east of the Huang He.

Samples

Participants in the study were selected from three rural towns in Qinghai Province in western China: Guinan, a county seat (altitude, 3,200 m), Maqin, a county seat and district capital (altitude, 3,800 m), and Mado, a county seat (altitude, 4,300 m). Sampling in towns, rather than among nomadic encampments, permitted a maximization of sample sizes necessary for statistical comparisons. In addition, the towns in which the participants lived shared similar socioeconomic characteristics, thus minimizing intra- and intergroup variability in nutrition, health care, and activity pattern.

Participants were recruited from local schools with the help of the county office of the Department of Maternal and Child Health, a division of the Qinghai Bureau of Public Health. Personnel from local health offices and hospitals assisted in explaining the procedures to school officials, teachers, and parents. The protocol for this study was reviewed and approved by the Human Subjects Committee of the Institutional Review Board at Temple University and by the Qinghai Bureau of Public Health.

Birthplaces and birth dates of participants between the ages of 6–29 years were determined from school records or other official forms of identification. These sources provided birth dates in terms of the Western calendar. In addition, individuals were asked if they had visited lower elevations in the year preceding the study, and the duration of that visit. Among younger individuals, this determination was made by questioning the parents directly. Individuals who had migrated to the study area before their first birthday were included, if both parents were residents of the study town. This situation occurred occasionally when a child of two residents was born in a hospital at a lower elevation. Individuals who had been born at lower elevations and migrated to the study site after age 1 year, and individuals who had spent more than 4 weeks at lower elevations during the year prior to the study, were not included. Thus, the sample consists of Tibetan children, adolescents, and young adults who were born in the study

TABLE 1. Sample sizes of Tibetan children, adolescents, and young adults

Males				Females		
Age group (years)	3,200 m	3,800 m	4,300 m	Age group (years)	3,200 m	3,800 m
6–7	16	22	5	6–7	20	23
8–9	19	21	15	8–9	23	27
10–11	21	21	11	10–11	21	21
12–13	21	15	24	12–13	19	24
14–15	17	23	28	14–15	20	23
16–17	24	24	12	16–17	17	22
18–19	15	17	13	18–19	20	23
20–29	22	13	9	20–29	17	15
Totals	155	156	117	Totals	157	178

towns, or who had moved to the study towns in their infancy with no more than a few weeks' travel to other elevations.

Individuals were asked to identify their ethnicity and the ethnicity, names, and birthplaces of both parents. Statements regarding the ethnicity of parents were verified by checking whether the parents had Tibetan names, where the parents had been born, and by consulting with individuals in the community (e.g., teachers and healthcare workers) who were familiar with the participants and their families. Surveys made during the study indicate that there were no marriages between Hui (Chinese Muslims) and Tibetans in any of the study towns. Some Han-Tibetan marriages exist in Guinan, but very few in Mado or Maqin. No such union encountered during the study had occurred prior to the 1960s, since most of the lowland Chinese moved into the research area subsequent to the mid-1960s. Individuals were classified as Tibetan only if both parents were identified as ethnic Tibetans. Individuals who could not unambiguously be identified as Tibetan and individuals with only one Tibetan parent were not included in the analysis.

Maqin and Mado are located west of the Huang He, and Tibetan residents are members of Golok tribal groups. Prior to the 1960s, there was little contact between Goloks and low-altitude Han in the high-altitude areas of Central Qinghai (Bowles, 1935; Ekvall, 1939; Rock, 1956; Rockhill, 1891; Rowell, 1983). Golok Tibetan participants therefore are unlikely to possess Han ancestors if both parents are Golok Tibetans. Guinan is located east of the Huang He and north of the region into which Mongol populations migrated during the 18th century. Tibetan residents of the Guinan area have been characterized as *not* having Mongolian ancestry (Rock, 1956). However, genetic analysis using molecular markers was not possible, since biological specimens were not permitted to leave China without prior approval. Thus, a complete lack of Mongolian ancestry among Guinan Tibetans cannot be confirmed.

Table 1 shows the distribution of samples at the three altitudes, arranged by age group and sex. Male samples exist at 3,200 m, 3,800 m, and 4,300 m, and female samples exist at 3,200 m and 3,800 m. Pediatricians and other healthcare professionals from collaborating Chinese institutions assessed the health status of prospective participants. Individuals who were identified as suffering from chronic illnesses were not included in the sample.

Measurements

A standard set of anthropometric measurements was taken on each participant, following guidelines suggested by Weiner and Lourie (1981). These included stature, weight, skinfolds measured at the triceps and subscapular sites, upper arm circumference, transverse chest diameter, anterioposterior chest diameter, and chest circumference. Participants progressed through a series of stations, manned by research personnel who were trained to take specific measurements. Stature was measured using a GPM anthropometer (Zurich, Switzerland) permanently fixed to a wall. Weight was determined by a balance scale that was tested regularly for accuracy. Thorax measurements were taken by a GPM spreading calliper. Circumferences were measured using a steel tape (Lufkin, Cooper Tools, Apex,

TABLE 2. Means and standard deviations of anthropometric variables among Tibetan males measured at 3,200 m, 3,800 m, and 4,300 m[1]

Variable and altitude	Age groups (years) 6–7		8–9		10–11		12–13		14–15		16–17		18–19		20–29	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Stature (cm)																
3,200 m	111.4	6.1	120.8	6.2	128.4	5.8	139.5	4.5	149.5	11.0	164.7	6.6	168.0	5.2	168.7	5.4
3,800 m	113.8	5.5	121.1	6.0	132.9	4.7	144.1	6.5	153.7	6.6	165.1	5.6	165.4	4.7	167.5	5.9
4,300 m	116.3	3.5	123.3	4.9	132.5	5.9	143.7	7.5	154.8	8.3	162.5	6.8	166.3	5.1	166.2	7.4
F ratio	1.78		0.94		4.14*		3.17*		2.14		0.72		1.06		0.56	
Weight (kg)																
3,200 m	18.6	2.6	22.4	2.4	26.3	3.1	31.1	3.2	38.1	6.6	52.3	5.4	56.6	4.7	57.5	5.3
3,800 m	18.8	2.3	22.3	4.3	27.8	4.5	34.3	5.8	43.3	5.7	53.3	5.5	55.7	4.0	57.8	6.4
4,300 m	20.9	2.6	23.0	1.8	27.6	2.4	34.5	5.5	42.0	7.6	52.3	6.5	54.8	5.5	58.0	5.0
F ratio	1.85		0.22		1.06		3.11*		3.04*		0.23		0.50		0.02	
Sum of skinfolds (mm)																
3,200 m	9.5	1.9	9.8	2.2	11.2	2.9	11.1	3.0	12.8	3.9	15.0	4.0	15.7	4.5	14.0	2.7
3,800 m	10.1	3.0	9.8	1.7	11.5	3.9	12.4	5.7	14.5	3.9	16.0	3.7	17.2	4.4	17.8	3.4
4,300 m	11.3	1.5	10.2	2.0	11.9	2.7	14.3	5.2	14.2	3.6	16.2	2.6	15.4	3.7	17.5	4.7
F ratio	1.03		0.16		0.16		2.67		1.11		0.68		0.77		4.76*	
Upper arm muscle area (cm^2)																
3,200 m	14.5	2.1	15.6	1.9	16.6	2.3	20.4	3.3	24.7	5.9	35.5	5.4	37.8	7.5	41.2	5.1
3,800 m	13.1	2.5	15.5	1.9	17.2	3.2	19.4	2.6	23.7	3.6	32.2	7.3	33.2	6.8	34.5	5.6
4,300 m	13.8	1.5	16.4	1.6	16.3	1.6	20.4	2.9	26.3	5.0	33.4	5.9	39.6	5.0	40.7	4.3
F ratio	1.80		1.21		0.47		0.65		1.89		1.61		3.90*		7.61**	

[1] F ratios for altitude differences are determined by an analysis of variance.
* $P > 0.05$.
** $P > 0.01$.

North Carolina). Skinfold measurements were taken using a Lange skinfold calliper (Cambridge, MD).

Cross-sectional muscle area of the upper arm was calculated, based on measurements of upper arm circumference and triceps skinfold, following a procedure described by Frisancho (1990). Chest shape was determined by dividing antero-posterior chest depth by transverse chest width, and multiplying the quotient by 100. Stature and weight are compared with U.S. growth standards (Frisancho, 1990) and with low-altitude Chinese growth standards, derived from the national growth study conducted in 1985 (State Education Commission et al., 1988).

Statistical analysis

Anthropometric data are aggregated into 2-year age groups, and statistical comparisons among age groups living at different altitudes are assessed by analysis of variance (Snedecor and Cochran, 1969). F ratios are presented for differences between the means of anthropometric measurements for each 2-year age group; the degree of statistical significance is noted at the $P < 0.05$, $P < 0.01$, and $P < 0.001$ level. Since thorax measurements are significantly affected by body size, between-altitude comparisons of chest width, chest depth, chest shape, and chest circumferences within age-groups are conducted using an analysis of covariance (Snedecor and Cochran, 1969). Stature is used as the covariant for altitude comparisons of chest width, chest depth, and chest shape. Chest circumferences are likely to reflect differences in muscle and fat, as well as ribcage size; hence stature, subscapular skinfold, and upper arm muscle area are used as covariates when altitude differences in chest circumferences are evaluated.

RESULTS

Tables 2 and 3 show the means and standard deviations of anthropometric variables for Tibetan males and females, arranged by age group. Stature differences between Tibetan males living at the three altitudes are only significant among 10–11- and 12–13-year-olds. The stature of 8–9-, 10–11-, and 12–13-year-old Tibetan females at 3,800 m is significantly greater than among Tibetans females at 3,200 m. The means and standard deviations of stature among Tibetan males and females, shown graphically in Figures 2 and 3, are generally below the

TABLE 3. Means and standard deviations of anthropometric variables among Tibetan females measured at 3,200 m and 3,800 m[1]

Variable and altitude	Age groups (years) 6–7		8–9		10–11		12–13		14–15		16–17		18–19		20–29	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Stature (cm)																
3,200 m	111.9	6.4	120.5	4.4	128.4	7.1	141.5	6.7	150.2	4.6	153.8	5.0	156.6	6.5	157.1	4.4
3,800 m	113.5	4.1	125.0	5.5	137.4	7.1	146.9	7.6	151.2	5.5	155.3	4.1	155.0	4.7	157.4	4.0
F ratio	0.99		9.78**		16.84***		6.08*		0.36		1.01		0.67		0.03	
Weight (kg)																
3,200 m	17.9	2.2	20.9	2.4	24.8	4.5	31.7	5.8	40.5	5.1	47.2	4.5	52.1	7.3	51.0	6.1
3,800 m	19.2	2.0	22.4	2.3	28.7	4.2	36.4	5.9	42.6	5.6	50.6	5.2	52.0	4.7	50.4	6.7
F ratio	4.46*		4.93*		8.28**		6.85**		1.67		4.68*		0.05		0.08	
Sum of skinfolds (mm)																
3,200 m	10.0	1.9	11.2	4.2	12.9	3.4	12.3	3.6	21.2	8.1	27.2	6.1	28.2	7.5	30.1	8.5
3,800 m	11.5	2.3	11.6	3.1	14.0	4.2	17.8	7.5	23.3	9.9	32.0	10.2	40.2	8.4	33.0	9.6
F ratio	4.89*		0.13		0.83		5.62*		0.55		2.89		24.11***		0.65	
Upper arm muscle area (cm^2)																
3,200 m	13.2	2.0	14.8	2.3	14.6	1.5	18.9	3.3	22.0	5.4	22.4	2.7	29.1	5.7	31.1	5.3
3,800 m	13.1	1.3	14.6	2.1	16.6	2.2	18.7	2.6	20.8	2.6	23.0	3.3	22.7	3.7	22.9	4.3
F ratio	0.06		0.16		10.68***		0.03		0.88		0.38		19.77***		21.91***	

[1] F ratios for altitude differences are determined by an analysis of variance.
* $P > 0.05$.
** $P > 0.01$.
*** $P > 0.001$.

U.S. 50th percentile for all age and sex groups. Tibetan boys and girls at 3,200 m tend to be shortest (approximating the U.S. 5th percentile). At 3,800 m, girls tend to be near the Chinese 50th percentile through age 13, while 6–13-year-old Tibetan boys at 3,800 m vary between the Chinese 50th percentile and the U.S. 5th percentile. The stature of Tibetan 14–15-year-old males and females is comparable to the U.S. 5th percentile, regardless of altitude; but among older individuals, stature increases relative to U.S. and Chinese standards, so that it is near the Chinese 50th percentile among young adults at all altitudes.

Weight differences among Tibetan males at the three altitudes are not statistically significant, while females at 3,800 m are generally heavier than females at 3,200 m. Figure 4 shows that the mean weight of males is between the Chinese 50th percentile and the U.S. 50th percentile, regardless of altitude and age group. Figure 5 shows that, for most age groups, Tibetan females at 3,800 m are above the Chinese 50th percentile for weight, while Tibetan girls at 3,200 m are at the U.S. 5th percentile. The mean weights of Tibetans females aged 18–19 and 20–29 are at, or just above, the Chinese 50th percentile, regardless of altitude.

Except for 20–29-year-olds, there are no altitude differences in the sum of triceps and subscapular skinfold thicknesses among Tibetan males. The mean sums of skinfolds among boys aged 14 years and older are comparable to the U.S. 50th percentile, while the mean sums of skinfolds among boys aged 13 years and younger are between the U.S. 25th and 5th percentiles. Females at 3,800 m tend to be somewhat fatter than females at 3,200 m, but differences are statistically significant only for 6–7-, 12–13-, and 18–19-year-olds. Females at 14 years and older tend to have skinfold thicknesses near the U.S. 50th percentile, while younger girls tend to have skinfold thicknesses near the U.S. 5th percentile.

Altitude differences in upper arm muscle area are not statistically significant among Tibetan males or among Tibetan females aged 17 years and younger. However, among 18–19- and 20–29-year-olds, males at 3,800 m have significantly smaller muscle areas than males at 3,200 m or 4,300 m, even when stature is entered as a covariate. Among Tibetan women, 18–19- and 20–29-year-olds from 3,800 m have significantly smaller muscle areas than 18–29-year-olds from 3,200 m.

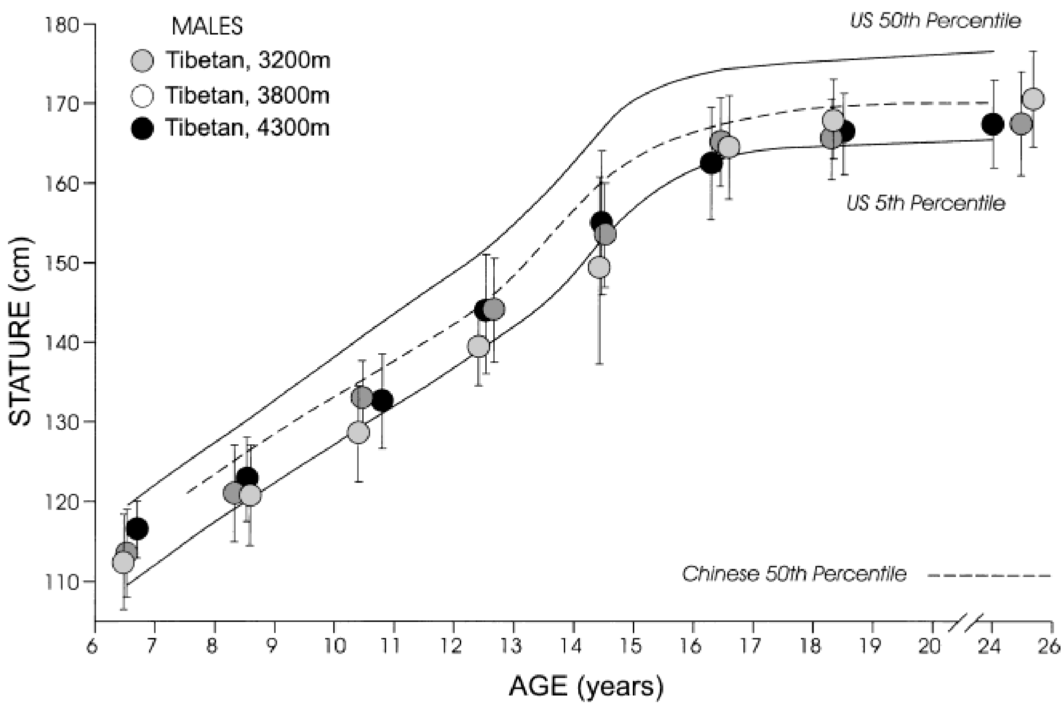

Fig. 2. Means and standard deviations for stature among Tibetan males born and raised at three different altitudes, compared to the 5th and 50th percentiles of U.S. children (Frisancho, 1990) and the 50th percentile of low-altitude Chinese children (State Education Commission et al., 1988).

Table 4 shows the results of an analysis of covariance for altitude differences in chest dimensions among Tibetan males. Age group means of chest width, chest depth, and chest shape (chest depth/chest width × 100) are adjusted for the effects of stature; age group means of chest circumference are adjusted for the effects of stature, subscapular skinfold, and upper arm muscle area. There are relatively few statistically significant altitude differences in chest width or chest depth among males. There is, nevertheless, a tendency for males at 4,300 m to have somewhat smaller chest widths and somewhat larger chest depths than males at 3,800 m and 3,200 m. Altitude differences in chest shape are statistically significant among males aged 12–15 years, and from 18–29 years. Chest circumferences, adjusted for differences in stature, upper arm muscle area, and subscapular skinfold, show few altitude-related differences. Analysis of covariance indicates that altitude differences are statistically significant only among 14- and 15-year-olds.

Table 5 shows the results of an analysis of covariance for altitude differences in chest dimensions among Tibetan females. Age group means of chest width, chest depth, and chest shape (chest depth/chest width × 100) are adjusted for the effects of stature; age group means of chest circumference are adjusted for the effects of stature, subscapular skinfold, and upper arm muscle area. In general, chest dimensions are similar among similarly aged Tibetan females living at 3,200 m and 3,800 m. Differences in stature-adjusted chest width means are not statistically significant for any age group. Except for girls aged 6 and 7 and 10 and 11, differences in stature-adjusted chest depth means are also not statistically significant. Altitude differences in chest shape are statistically significant only among females aged 8 and 9, and 14 and 15. Altitude differences in chest circumference are not statistically

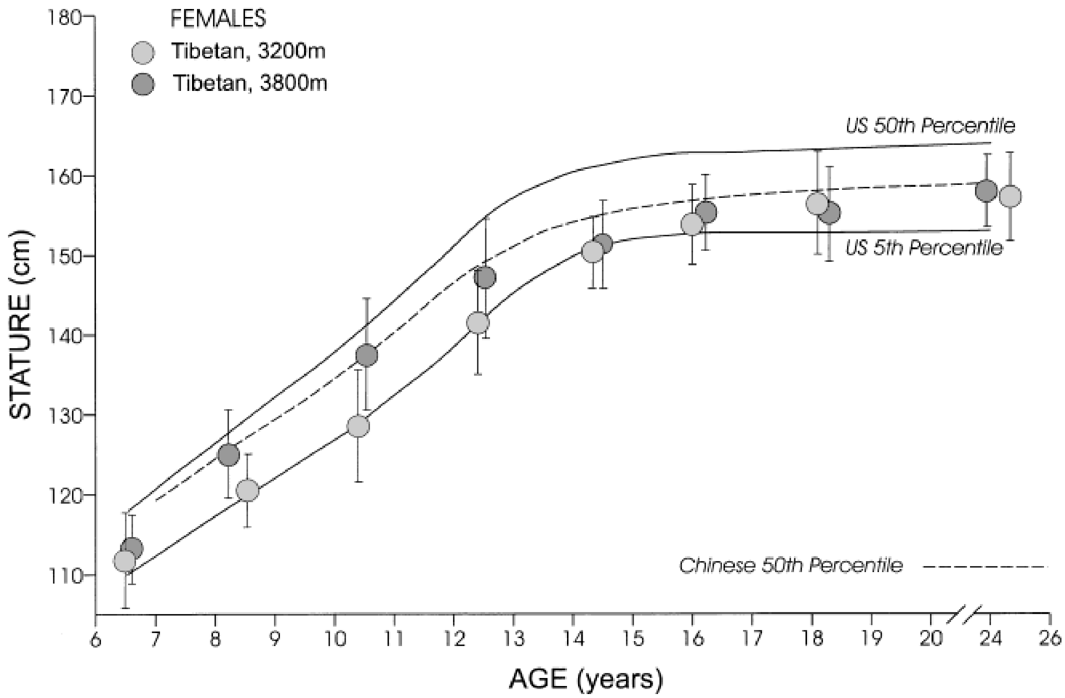

Fig. 3. Means and standard deviations for stature among Tibetan females born and raised at two different altitudes, compared to the 5th and 50th percentiles of U.S. children (Frisancho, 1990) and the 50th percentile of low-altitude Chinese children (State Education Commission et al., 1988).

significant, except among 16- and 17-year-old females.

DISCUSSION

Body size

In the past 30 years, several cross-sectional growth studies have been conducted among Tibetan children and adolescents living at high altitude. The average statures of Tibetan males and females from previously published studies and of Qinghai Tibetan males and females are shown in Figures 6 and 7. Tibetan males and females in this study are approximately as tall as Tibetans growing up at 3,560 m in Lhasa (Ji and Ohsawa, 1993). Qinghai Tibetan boys are generally taller and heavier than boys from the Bod population living at 3,514 m in Ladakh district, northern India (Malik, 1987; Malik and Pandey, 1993; Malik and Singh, 1978, 1984), boys living between 3,250–3,650 m in the Upper Chumik region of north-central Nepal (Beall, 1984), and Sherpa boys living between 3,475–4,050 m in the Khumbu region near Mt. Everest (Pawson, 1974, 1977a). Qinghai Tibetan girls are slightly taller than Bod adolescent girls (Malik and Pandey, 1993), and consistently taller than Upper Chumik (Beall, 1984) and Sherpa (Pawson, 1974) girls.

Despite these differences, the statures of all Tibetan groups shown in Figures 6 and 7 fall below U.S. norms, with only the very tallest groups being barely equivalent to the U.S. 5th percentile. This relatively small size might be an expected consequence of the delay in linear growth that has been attributed to the effect of hypoxia at high altitude (Greksa, 1990). However, previous studies comparing children from Tibetan-speaking populations who were born and raised at low and high altitudes have not provided much support for this hypothesis. Pawson (1974, 1977a) reported that there were no basic differences in stature, weight, or skinfold thicknesses between Tibetan children grow-

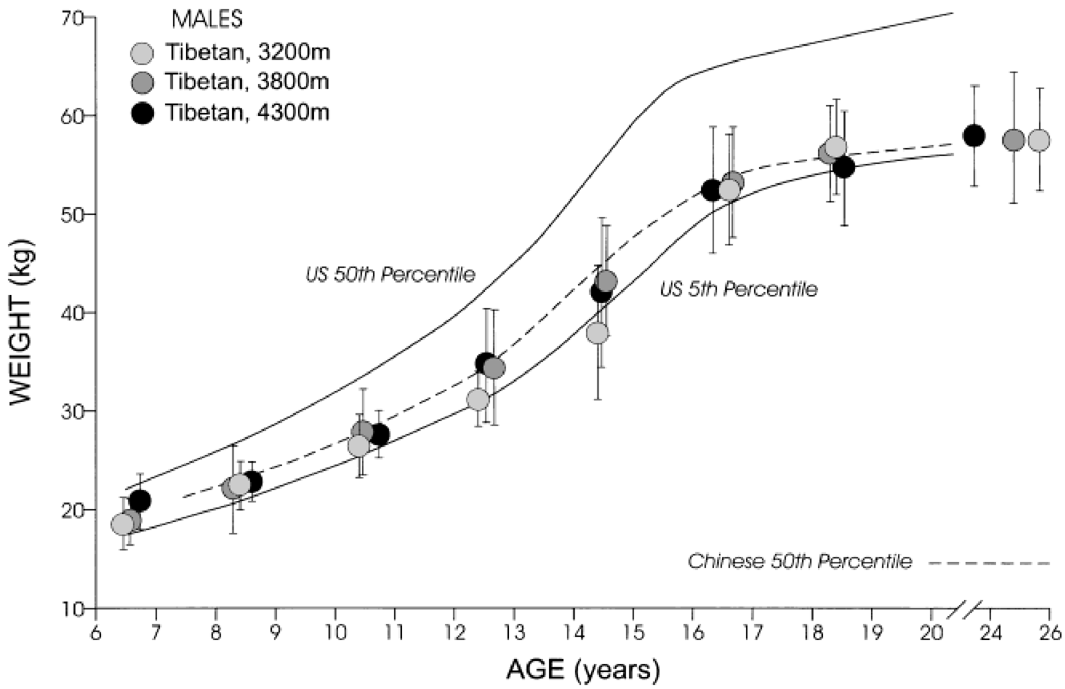

Fig. 4. Means and standard deviations for weight among Tibetan males born and raised at three different altitudes, compared to the 5th and 50th percentiles of U.S. children (Frisancho, 1990) and the 50th percentile of low-altitude Chinese children (State Education Commission et al., 1988).

ing up at 1,000 m near Kathmandu and Sherpa children from the high-altitude Khumbu region of Nepal. In a study comparing Sherpa children living in the Khumbu and children from the Kalimpong area of northeastern India (1,000–1,500 m), Gupta and Basu (1991) indicate that stature differences are relatively modest, although the high-altitude group may experience a slower and more prolonged period of growth than the low-altitude children and adolescents. Malik and Singh (1984) report that Tibetan-derived Bod boys born and raised at high altitude are somewhat taller and heavier after age 13 compared to Bod boys born and raised at 1,400 m, but differences are not statistically significant until age 19. Among Bod girls, altitude differences in stature are not statistically significant; but those born at the lower elevation were significantly heavier after age 13 than those residing at the higher elevation (Malik and Pandey, 1993).

Similarly, this study does not provide support for the hypothesis that growth is negatively effected by altitude differences above 3,000 m. Among Qinghai Tibetans living at 3,200 m (P_B = 525 mm Hg), at 3,800 m (P_B = 484 mm Hg), and at 4,300 m (P_B = 457 mm Hg), statistically significant differences exist for stature and weight among boys between ages 10–13, and girls between ages 8–13, but not among older or younger individuals. Moreover, the shortest and lightest boys and girls in these age groups do not live at the highest altitude (4,300 m), but at the lowest altitude (3,200 m)—the opposite of what might be expected if hypoxia were a major cause of morphological variation between altitudes.

It might be possible to attribute altitude variation in height and weight to genetic differences between Golok Tibetans living at 3,800 m and 4,300 m and non-Golok Tibetans living at 3,200 m. To the extent that these two groups might represent biologically distinct populations, the existence of a single Golok gene pool might then explain the similar weights and heights of children living at 3,800 m and 4,300 m, despite

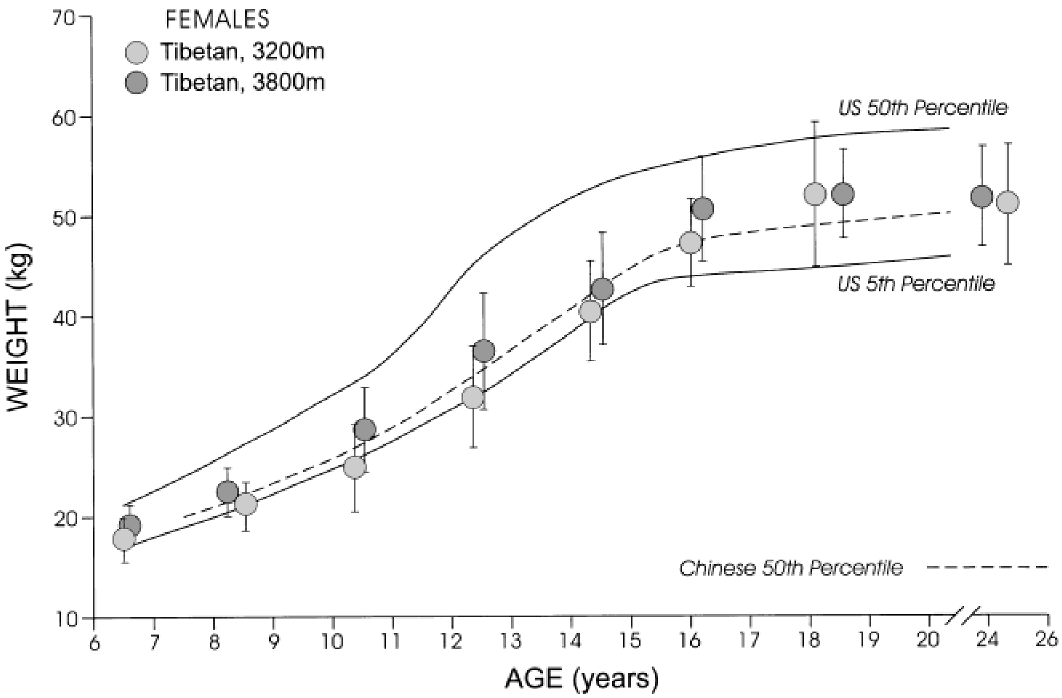

Fig. 5. Means and standard deviations for weight among Tibetan females born and raised at two different altitudes, compared to the 5th and 50th percentiles of U.S. children (Frisancho, 1990) and the 50th percentile of low-altitude Chinese children (State Education Commission et al., 1988).

differences in altitude. Analogously, the smaller stature of children living at 3,200 m might then be attributed to the distinct biological nature of non-Golok Tibetans. The problem with this interpretation is that the most significant height and weight differences exist around the time when puberty is likely to occur. Among older adolescent and young adult females, there are no altitude-related differences in stature or weight; and there are no altitude-related differences in stature or weight among young boys, or among older adolescent and young adult males. Since adults of both sexes achieve similar size, regardless of location or group affiliation, an alternative explanation is that the onset of the adolescent growth spurt is retarded among Qinghai Tibetan children living at 3,200 m (relative to children living at 3,800 m and 4,300 m), for reasons not associated with genetics or hypoxia.

Poor nutrition and/or healthcare cause growth retardation at high altitude, just as at low altitude. Indeed, studies in Peru indicate that nutrition may be a more significant cause of reduced growth at high altitude than hypoxia (e.g., Obert et al., 1994; Leonard et al., 1990). In Asia, it is noteworthy that two of the Tibetan groups represented in Figures 6 and 7 have shown significant secular trends in growth. In 1982, Sherpas between the ages of 5–12 were up to 8 cm taller and 5 kg heavier than Sherpa children measured in 1971 (Pawson et al., 1989). Tibetans growing up in Lhasa in 1991 were between 6–12 cm taller and between 3–8 kg heavier than children and adolescents measured in 1965 (Ji and Ohsawa, 1993). In both cases, increases in stature, weight, and skinfold thickness coincided with improved nutrition and healthcare, which were associated with significant socioeconomic changes (Pawson et al., 1984; Ji and Ohsawa, 1993).

In this study, some proximate differences in calories available to children and adolescents at the different altitudes are indicated by skinfold measurements. The sums of

TABLE 4. Results of analysis of covariance for altitude differences in chest dimensions among Tibetan males measured at 3,200 m, 3,800 m, and 4,300 m[1]

	Age groups (years)							
Variable and altitude	6–7, adjusted mean	8–9, adjusted mean	10–11, adjusted mean	12–13, adjusted mean	14–15, adjusted mean	16–17, adjusted mean	18–19, adjusted mean	20–29, adjusted mean
Chest width (cm)								
3,200 m	18.2	19.3	20.4	22.0	23.4	26.5	27.2	28.4
3,800 m	17.8	19.0	20.4	22.2	24.0	26.8	26.8	27.4
4,300 m	17.9	18.5	19.9	21.5	23.4	25.6	26.9	27.5
F ratio	0.91	2.83	0.85	1.79	2.52	3.80*	0.29	1.45
Chest depth (cm)								
3,200 m	13.2	13.6	14.0	15.0	16.7	17.9	18.2	19.4
3,800 m	12.8	13.5	13.9	15.1	16.3	18.2	18.6	19.3
4,300 m	13.2	13.5	14.3	15.6	16.9	18.3	19.1	20.0
F ratio	2.24	0.14	0.53	2.50	2.39	0.52	2.67	0.83
Chest depth/chest width × 100								
3,200 m	72.2	70.6	69.0	68.1	71.2	67.8	67.4	68.6
3,800 m	72.1	71.1	68.3	68.5	68.1	68.0	69.5	70.2
4,300 m	74.7	73.0	72.1	72.6	72.5	71.5	71.2	72.9
F ratio	0.78	1.94	2.37	5.01**	7.37***	2.42	3.93*	4.21*
Chest circumference (cm)								
3,200 m	55.3	58.7	61.7	66.7	70.1	80.8	81.4	85.5
3,800 m	55.5	58.7	60.4	66.0	74.2	81.2	81.5	86.3
4,300 m	57.7	58.3	62.3	67.3	73.1	81.6	83.6	87.7
F ratio	1.93	0.16	2.62	1.34	8.49***	0.29	2.48	1.30

[1] Means of chest width, chest depth, and chest depth/chest width are adjusted for differences in stature. Means of chest circumference are adjusted for differences in stature, subscapular skinfold, and upper arm muscle area. F ratios are for altitude differences, after controlling for covariates.
*$P > 0.05$.
**$P > 0.01$.
***$P > 0.001$.

TABLE 5. Results of analysis of covariance for altitude differences in chest dimensions among Tibetan females measured at 3,200 m and 3,800 m[1]

	Age groups (years)							
Variable and altitude	6–7, adjusted mean	8–9, adjusted mean	10–11, adjusted mean	12–13, adjusted mean	14–15, adjusted mean	16–17, adjusted mean	18–19, adjusted mean	20–29, adjusted mean
Chest width (cm)								
3,200 m	17.5	19.1	20.1	22.4	23.8	25.1	25.6	25.8
3,800 m	17.9	18.7	20.5	22.1	22.4	25.1	25.4	25.7
F ratio	3.38	2.31	1.35	0.30	1.75	0.01	0.25	0.09
Chest depth (cm)								
3,200 m	12.1	12.6	13.2	15.1	15.1	16.3	17.0	17.7
3,800 m	12.6	13.0	13.8	14.8	15.5	16.6	17.1	17.6
F ratio	4.31*	3.53	5.41*	0.75	2.76	0.40	0.06	0.29
Chest depth/chest width × 100								
3,200 m	69.3	66.1	65.5	67.6	63.3	65.1	66.7	68.7
3,800 m	70.3	69.4	67.5	67.0	66.6	65.9	67.2	68.0
F ratio	0.82	8.42**	1.45	0.14	5.53*	0.45	0.17	0.47
Chest circumference (cm)								
3,200 m	54.2	57.5	60.1	66.4	72.2	79.3	80.8	80.7
3,800 m	53.7	56.6	60.9	65.0	71.1	76.3	78.2	80.0
F ratio	0.55	1.86	0.86	2.08	0.64	6.69*	2.40	0.11

[1] Means of chest width, chest depth, and chest depth/chest width are adjusted for differences in stature. Means of chest circumference are adjusted for differences in stature, subscapular skinfold, and upper arm muscle area. F ratios are for altitude differences, after controlling for covariates.
* $P > 0.05$.
** $P > 0.01$.

triceps and subscapular skinfolds are generally lower among females and, to a somewhat lesser extent, among males at 3,200 m than at the other two altitudes. But the extent to which this reflects long-term nutritional differences is unclear. In the present study, there are no differences in muscle mass among males and most females under

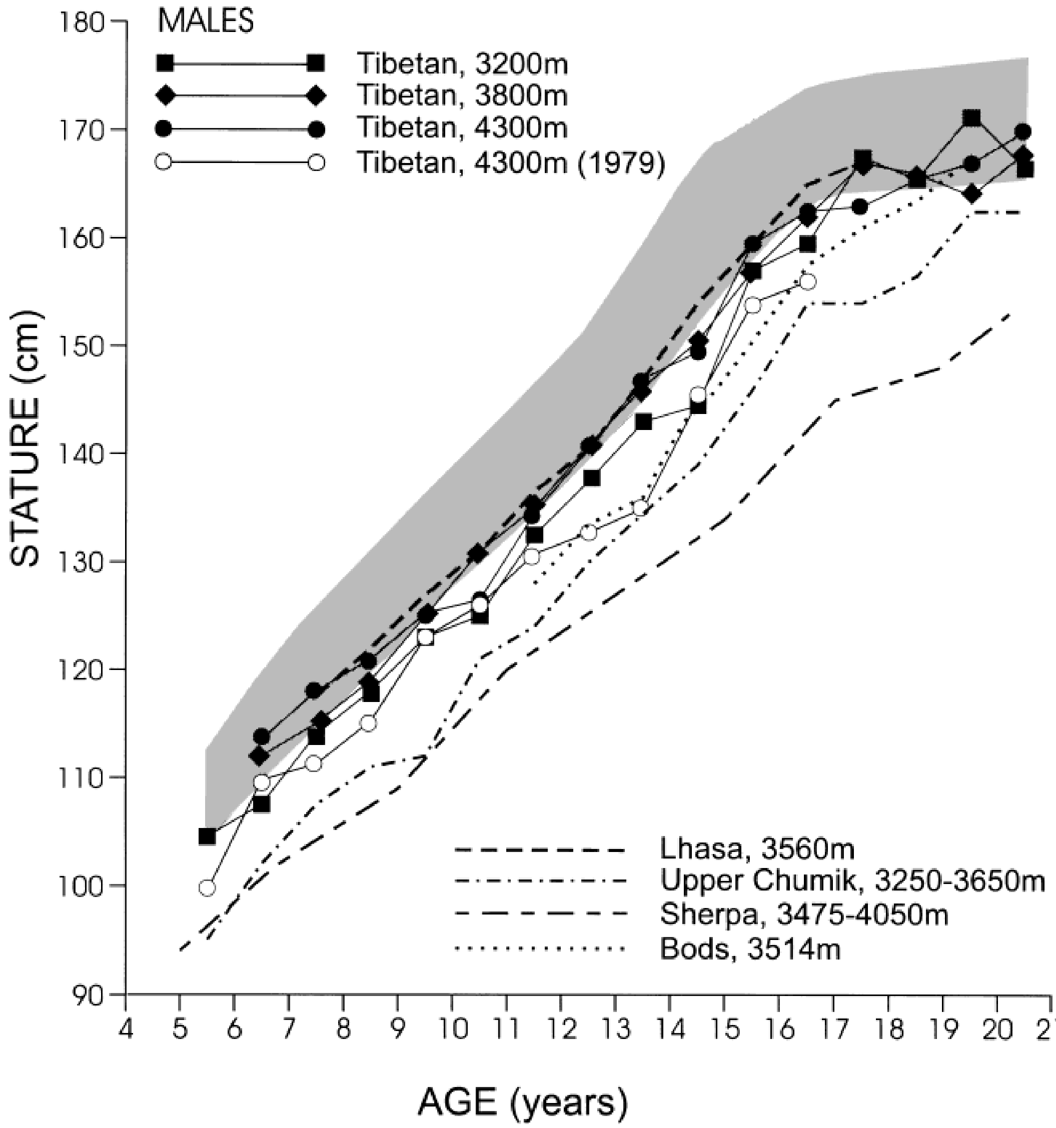

Fig. 6. Stature of Qinghai Tibetan males at three different altitudes, compared with Tibetan males measured in Lhasa (Ji and Ohsawa, 1993), Tibetan males measured in Upper Chumik (Beall, 1984), Bod males measured in Ladakh (Malik, 1987; Malik and Pandey, 1993; Malik and Singh, 1978, 1984), Sherpa males measured in the Khumbu region of Nepal (Pawson, 1974, 1977a), and Qinghai Tibetan males measured at 4,300 m in 1979 (Kuang, 1980). Shaded area represents the 5th–50th percentiles for stature among U.S. boys.

age 18, regardless of altitude; thus, the existence of differences in access to protein is unlikely. On the other hand, evidence exists for a secular increase in growth rates at 4,300 m. In 1979, Tibetan boys, aged 11–16 years and living in Mado (Kuang, 1980), were between 4–8 cm shorter, and between 3–7 kg lighter than similarly aged boys measured in the present study. Figure 6 shows that Tibetan boys measured at 4,300 m in 1979 were even shorter than boys measured at 3,200 m in the present study. At 4,300 m, the differences in stature between the 1979 study and measurements reported here suggest that events that occurred during the 1980s and early 1990s may have had

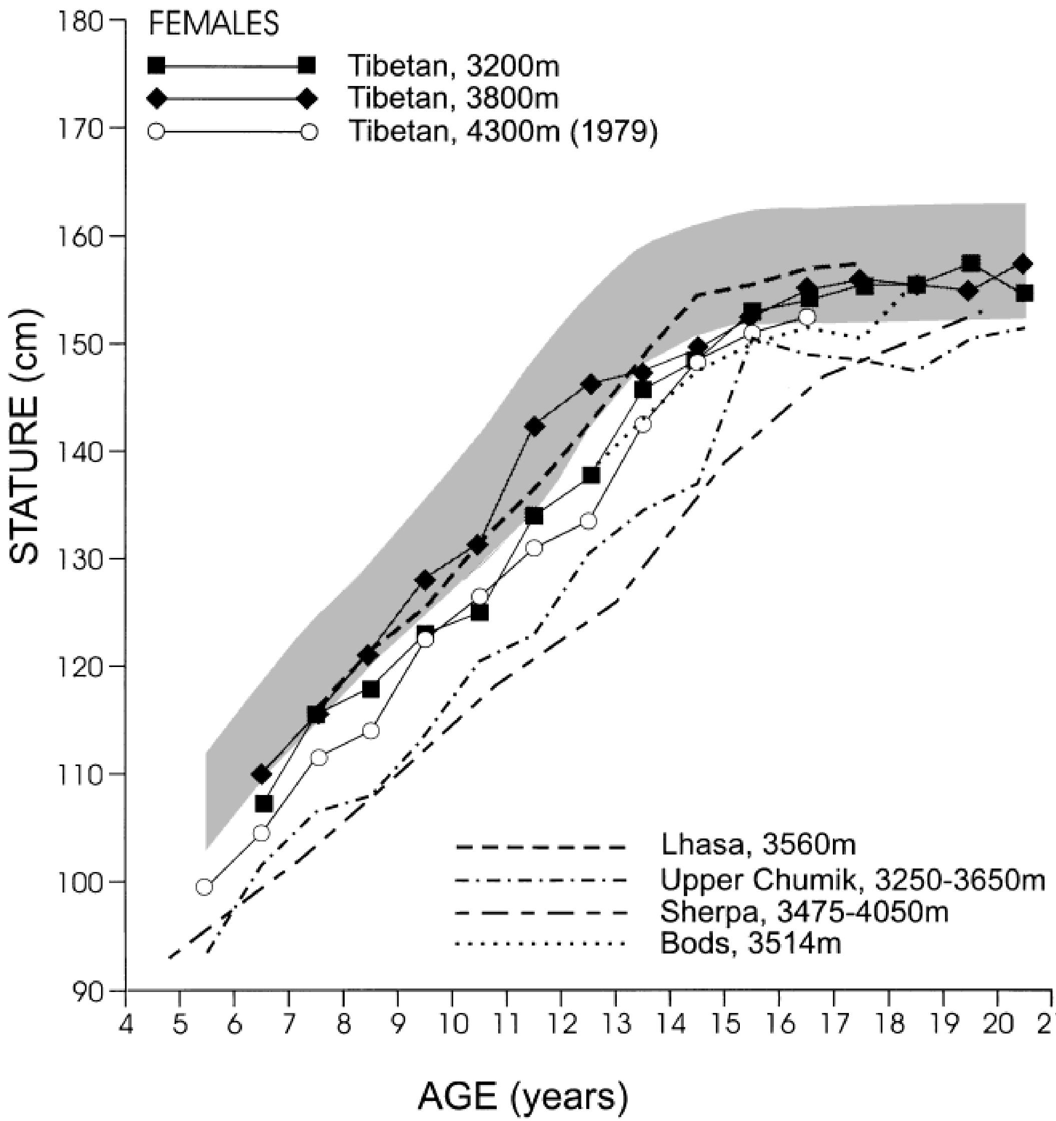

Fig. 7. Stature of Qinghai Tibetan females at two different altitudes, compared with Tibetan females measured in Lhasa (Ji and Ohsawa, 1993), Tibetan females measured in Upper Chumik (Beall, 1984), Bod females measured in Ladakh (Malik, 1987; Malik and Pandey, 1993; Malik and Singh, 1978, 1984), and Sherpa females measured in the Khumbu region of Nepal (Pawson, 1974, 1977a). Shaded area represents the 5th–50th percentiles for stature among U.S. girls.

a significant impact on the health and nutrition of children living there. The construction of paved roads, decollectivization of land and animal ownership, and growing economic and political integration with the provincial capital all occurred during this period. It is therefore possible that recent economic changes have been more rapid or pervasive in Mado (a major political and economic center on the road between Xining and Lhasa) and Maqin (also a regional capital) than in Guinan. A slower pace of economic change, associated with somewhat poorer nutrition and healthcare, may be responsible for the delayed onset of the adolescent growth spurt at 3,200 m. Thus, in

Asia as in Peru, differences in nutrition and health condition may play a greater role in explaining differences in growth than altitude variation.

Chest morphology

Much of the interest in growth at high altitude in Asia has focused on the thorax, particularly after Beall (1982) noted that chest dimensions of the Tibetan-speaking, Mugu population living in northwestern Nepal were smaller than those of the high-altitude Quechua population living in the Andes. Other growth studies in which chest dimensions are reported tend to show the same pattern. Children and adolescents in Upper Chumik have smaller chest depths relative to stature than either Peruvian Quechua or Bolivian Aymara children (Greksa and Beall, 1989). Among the Khumbu Sherpas, chest circumferences are also smaller than among the Quechua, particularly after age 13 (Pawson, 1977b). Chest circumferences relative to stature among Bod adolescent males (Malik and Singh, 1978) are similar to those reported for Sherpa boys (Pawson et al., 1984), while the chest widths of adolescent Bod males (Malik, 1987) are similar to those of boys from Mugu (Beall, 1982).

Figures 8 and 9 compare chest width and chest depth measurements relative to stature among Tibetan males and females between ages 5–29 years. Stature is used as the dependent variable in these graphs, rather than age, because chest measurements are highly correlated to differences in stature (DeGroodt et al., 1988; Rosenthal et al., 1993), and because stature differences among individuals of the same age can be significant within and between some of the Tibetan groups shown. Qinghai Tibetan males, and Tibetan males from Ladakh (Malik, 1987), Upper Chumik (Greksa and Beall, 1989) and Mugu (Beall, 1982), show similar chest widths relative to stature. Among Qinghai males under age 18, chest depths are smaller than those of Bods and Mugu Tibetans of comparable stature, but similar to those reported for Tibetans from Upper Chumik. On the other hand, chest depths of Qinghai males age 18 and over, particularly those from 4,300 m, are within one standard deviation of the means for Bod and Mugu males of comparable stature. Qinghai Tibetan females under 18 years show smaller chest widths and chest depths than Mugu women of comparable stature. However, the chest dimensions of older adolescents and young adults are similar to those of older Mugu females of comparable stature. Thus, the results of this study provide additional support for the hypothesis that chest width and depth of high-altitude Tibetans are smaller than those reported for high-altitude Andeans.

Nevertheless, these cross-sectional data indicate that chest depths among Qinghai Tibetans of both sexes and chest widths among Qinghai Tibetan females are smaller, relative to stature, than those of other Tibetan groups during early and middle adolescence, but equivalent to those of other Tibetan groups during late adolescence and early adulthood. Studies of different high-altitude populations (Beall, 1982), and of highlanders vs. lowlanders of the same ethnicity (Beall et al., 1977; Mueller et al., 1978), also indicate that thorax differences tend to be greater during adolescence than among adults. Variations in adolescent vs. adult thorax size may be associated with differences in the timing and the duration of the adolescent growth spurt. During adolescence at low altitude, the thoracic index (chest depth/chest width) declines among boys and remains constant among females (Takahashi and Atsumi, 1955). However, in both boys and girls, thorax height increases more quickly than width or depth, so the width and depth of the thorax decrease relative to thorax length in both sexes (DeGroodt et al., 1988; Grivas et al., 1991). Thus, individuals who are in the midst of their adolescent growth spurt will have narrower and (particularly among males) shallower chests, relative to thorax length, than those who have not yet begun the growth spurt. Likewise, individuals whose adolescent growth is delayed due to nutritional, disease, or environmental stress would be expected to have wider and deeper chests (relative to thorax length) than individuals of the same age who already have begun their spurt. Using this model, the different thorax dimensions among adolescents noted

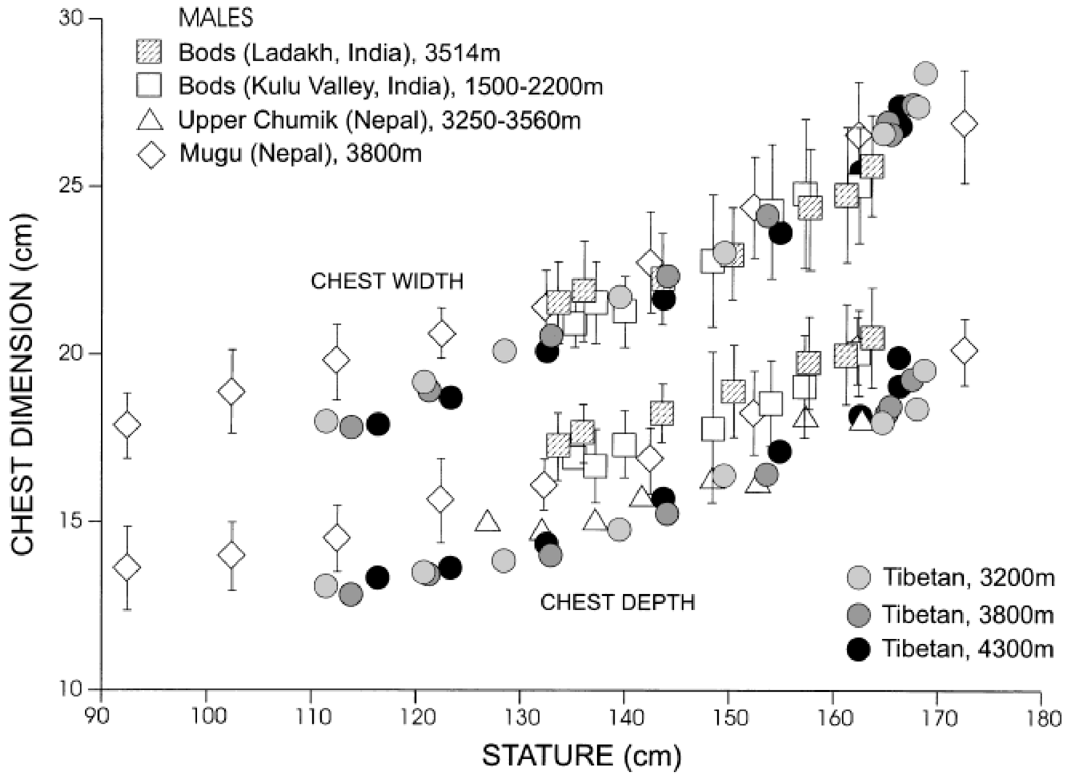

Fig. 8. Means and standard deviations of chest width and chest depth relative to stature among Tibetan males at three different altitudes, compared to Bod males from Ladakh and the Kulu Valley (Malik, 1987). Tibetan males from the Mugu region of Nepal (Beall, 1982), and Tibetan males from Upper Chumik (Greksa and Beall, 1989).

in Figures 8 and 9 could be explained by an earlier onset of the adolescent growth spurt among Qinghai Tibetans than among Tibetans from Ladakh or Mugu—possibly a consequence of nutritional differences among populations, similar to those described above. Since the timing of the adolescent growth spurt affects the rate of change in thorax proportions, not the existence of changes, all groups should eventually show more similar thorax sizes as they proceed through adolescence and into adulthood.

Of course, this model presumes that there are no population differences in thorax growth, or in the growth of body proportions that could affect thorax-to-stature ratios. Both presumptions may be violated among Qinghai Tibetan and other high-altitude populations. In Peru, chest dimensions are similar among highland and lowland Quechua, despite differences in stature (Beall et al., 1977; Hoff, 1974), indicating that genetic factors may regulate thorax growth in this population (Beall et al., 1977). In Bolivia, increased chest depth among individuals at higher elevations has been linked to Aymara ancestry (Mueller et al., 1978; Palomino et al., 1979). Similarly, despite some altitude differences, Bods appear to show large chest depths relative to stature at both lower and higher elevations, compared to other Asian high-altitude groups. In Qinghai, however, a genetic explanation appears unlikely, since relatively small thoraxes occur among both Golok and non-Golok Tibetans. Besides, Golok males at 4,300 m appear to possess deeper and narrower chests that Golok males at 3,800 m, a difference that would not be predicted by a genetic model.

Alternatively, hypoxia may alter the growth of thorax dimensions independently of genetic factors. In Qinghai, only minor

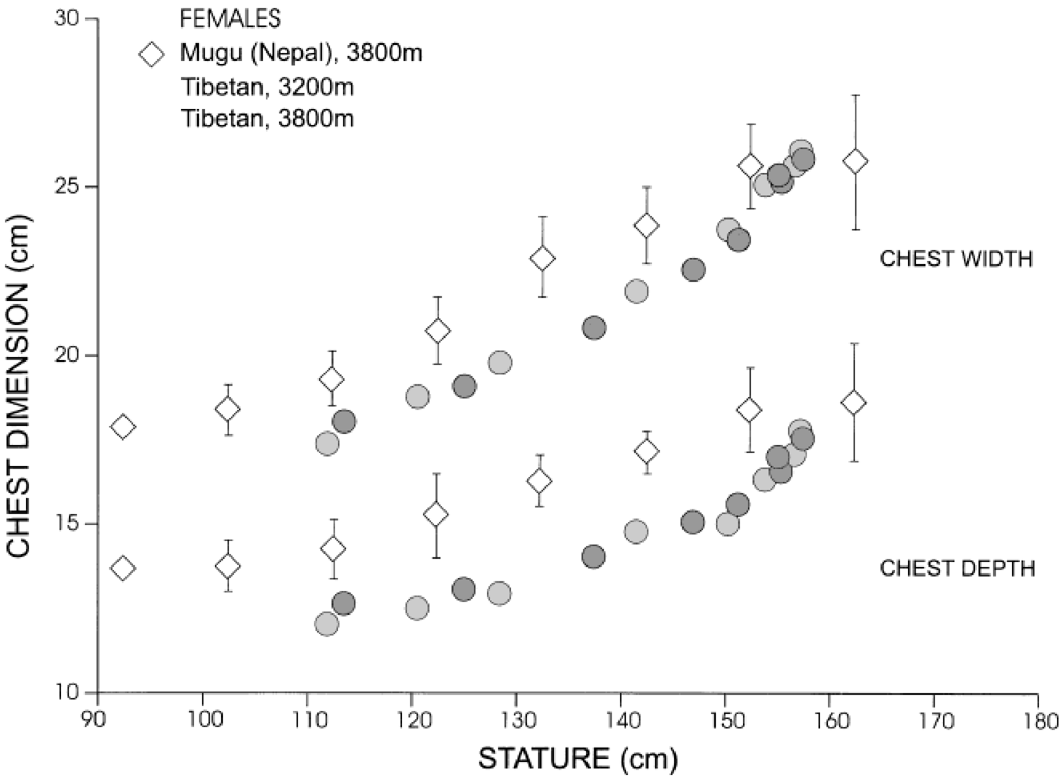

Fig. 9. Means and standard deviations of chest width and chest depth relative to stature among Tibetan females at two different altitudes, compared to Tibetan females from the Mugu region of Nepal (Beall, 1982).

differences in chest width and chest depth (relative to stature) exist between Tibetan males or among Tibetan females living at 3,200 m and 3,800 m. At 4,300 m, however, males have slightly narrower and deeper chests than males at 3,800 m and 3,200 m. This results in a significantly greater ratio of chest depth to chest width at 4,300 m than at the two lower elevations. Altitude-related increases in chest depth relative to chest width also have been noted among Aymara children growing up at high altitude in the Andes (Mueller et al., 1978), as well as among children of low-altitude European descent growing up at high altitude (Greksa, 1988). Furthermore, as indicated in Figure 8, Bods living at 3,514 m appear to have deeper but not wider chests, relative to stature, than Bods living between 1,500–2,200 m in the Kulu valley (Malik, 1987).

Finally, differences in thorax dimensions among Qinghai Tibetan males at 4,300 m compared to lower altitudes, and differences between Qinghai Tibetans and other high-altitude Asian populations, may reflect variable patterns of growth in thorax length. Although not shown here, males at 4,300 m have significantly larger sitting heights and sitting-height-to-stature ratios than males at 3,800 m or 3,200 m. This pattern persists through young adulthood, so it is not simply the result of differences in the timing of adolescent growth. From this perspective, the apparent similarity in thorax dimensions relative to stature achieved by older individuals in different populations (shown in Fig. 8) may be an artifact of differences in body proportions. Among 12- and 13-year-olds, for example, Qinghai Tibetan boys are approximately 10 cm taller than Bod boys (the only other group represented in Fig. 8 for which sitting height data are published; Malik, 1987), and have sitting heights that are 6 cm greater. At this age, one could

attribute the relatively shallower chest depth of Qinghai boys to more rapid growth in thorax length than in depth due to an earlier onset of the adolescent growth spurt, similar to what would be predicted by the model outlined above. However, older adolescent and young adult Qinghai males, particularly those from 4,300 m, continue to have greater sitting heights relative to stature than Bod males. Hence, chest depth relative to sitting height among older Bods is greater than among older Qinghai males, even though chest depth relative to stature is similar. This indicates that Qinghai males may have shallower and longer thoraxes than Bods at all ages.

The functional significance of population differences in relative and absolute thorax width, depth, and length is far from clear. Growth in the length of the thorax has been associated with increases in residual volume, vital capacity, and other lung volumes (DeGroodt et al., 1988; Rosenthal et al., 1993). This may indicate that increases in lung size associated with the growth of thorax length contribute to changes in compliance and recoil (DeGroodt et al., 1988; Openshaw et al., 1984), thereby producing larger lung volumes. However, variation in muscular strength during adolescence also contributes to changes in lung function, even among individuals of the same size (Engstrom et al., 1983; Rosenthal et al., 1993). Greater relative chest depth among the Aymara has been associated with increases in peak flow rates (Mueller et al., 1978). Greksa et al. (1987) reported that chest shape (chest depth/chest width) was positively correlated with FVC among female Aymara highlanders, and positively correlated with FEV_1/FVC ratios among male Aymara highlanders. But among highland and lowland Quechua, maximum flow rates are similar despite larger lung volumes among the highlanders (Brody et al., 1977). Furthermore, increases in chest depth relative to chest width also have been noted in pathological conditions. Individuals with COPD (Cassart et al., 1996) and long-term cigarette smokers (Borkan et al., 1981) develop more "rounded" chests shapes, possibly to accommodate chronic hyperinflation or because of loss of elastic recoil. Additional confusion arises because lung volumes, flow rates, pulmonary diffusion, and possibly alveolar number are significantly greater than predicted among swimmers, who exercise for protracted periods with low levels of arterial oxygen saturation, but who show increases in relative chest width rather than chest depth (Armour et al., 1993).

This analysis indicates that thorax growth at high altitude requires further attention in order to determine the genetic and environmental sources of variability among Asian high-altitude populations. At a minimum, a clearer understanding should be developed of the extent to which microenvironmental conditions (particularly indoor environmental pollution) and nutrition (Brody and Vaccaro, 1979) contribute to changes in thorax dimensions and shape during child and adolescent growth. For this purpose, it makes sense to use sitting height, rather than stature, as a measure of thorax length (Rosenthal et al., 1993), since individuals who possess the same thorax width, depth, and length, but who have different leg lengths, will have different widths and depths relative to stature. Finally, a growing body of evidence indicates that the world's high-altitude populations possess a variety of thorax sizes and shapes. Understanding why (or if) different lung/thorax forms can function equally well at high altitude is just as pressing a problem to resolve as whether population differences are due to genetic or environmental factors.

CONCLUSIONS

In this, as in all other studies of Tibetan populations, children and adolescents are smaller than is the case among well-off, low-altitude groups. However, the data presented here do not offer support for the hypothesis that variations in the degree of hypoxia at altitudes above 3,200 m affect the body size of Qinghai Tibetans. As has been noted among Andean children, growth of Tibetan males and females at high altitude in Qinghai may be more influenced by nutrition than by hypoxia. Like other high-altitude Asian populations, chest dimensions relative to stature are smaller than those reported for Andean populations. Altitude differences between 3,200 m and 3,800

m do not seem to greatly influence thorax dimensions. On the other hand, males at 4,300 m have narrower, shallower, and longer thoraxes than males at 3,200 m and 3,800 m; and Qinghai Tibetans may have shallower and longer thoraxes than other high-altitude Asian populations. The significance of these differences will have to await more complete studies of thorax growth and a more systematic effort to understand whether such differences have functional consequences.

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